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HEAT-RESISTANT CHROMIUM STEELS FOR SERVICE AT 550-600 DEGREES

Metallovedeniye i Obrabotka Metal-
Moscow, U.S.S.R., Jun 1956, pp
10-25

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[Numbers in parentheses refer to appended references. Tables and figures referred to are also appended.]

Pearlitic and austenitic class steels are used, depending on the temperature, for the most vital parts of steam turbines: rotors, bolts, and blades. The former are used for service at 550-560°; their use above these temperatures is limited by their inadequate heat resistance and heat stability.

Austenitic steels are used primarily for service at temperatures over 600°. These steels may also be used at 550-600° although their use at these temperatures would not be economically expedient. The necessity has therefore emerged for comparatively inexpensive steels which would satisfy requirements for heat resistance and heat stability at 550-600°.

England and the US are conducting research on ferritic-martensitic steels alloyed with 12% chromium with admixtures of hardening elements, primarily carbide-forming elements, which would limit the range of the γ -state: Mo, V, W, Nb, Ti, etc. (1-3). Published data indicate that such steels have a continuous strength of 17-24 kg/mm² and 7-10.5 kg/mm² at 540 and 595°, respectively. It is noted that some steels may be used for service at temperatures up to 600° in turbine disks, blades, and even rotors.

In conjunction with this, the authors conducted an investigation into the structural properties and heat-resistance characteristics of stainless steels with 12% chromium and various admixed elements.

The chemical composition of some of the investigated steels is shown in Table 1. All the steels were smelted in a 40-kg high-frequency furnace (except steels 15Kh12MFB and 15Kh12V1FBT, which were smelted in a 150-kg furnace). Rods were forged from the ingots; the rods were 40 x 40 mm in cross section with a ratio of cross-sectional area to the original ingot of 7 in the smaller rods and 30-35 in the bigger rods.

Figure 1 shows the relationship between the hardness of the steels and the oil hardening temperature. From Figure 1a it follows that in the first five steels (see Table 1), maximum hardness is attained in hardening from 1,000°; when the carbon content is 0.28%, the hardness is 450-500 H_B and is 360-420 H_B at 0.11-0.18% C. When the carbon content is at the lower level, additional alloying with niobium decreases hardness while the admixture of nitrogen and boron (15Kh12MFBT) increases it somewhat. Some steels attain their greatest hardness when hardened from 950-1,000°, and others when hardened from 1,000-1,050° (Figure 1b).

Characteristic of the steels investigated is that the hardness of some of the steels is noticeably decreased when they are hardened from temperatures in excess of 1,000-1,050° (for example, steels 15Kh12MF, 15Kh12MFB, 15Kh12VMFT, etc.).

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An investigation of the microstructure of the steels after various heat-treatments (hardening from various temperatures and tempering) showed the following.

Steels 25Kh12VF and 25Kh12MF had an identical structure of uniformly distributed sorbitic pearlite (see Figure 2a). An increase in the hardening temperature leads to the formation of some structurally free ferrite (see Figure 2b). When the carbon content is decreased to 0.18%, free areas of ferrite are formed (see Figure 2c).

Such steels as 15Kh12VMFT, 15Kh12MFB, 15Kh12VMFBT, and 15Kh12V1FBT have a considerable quantity of ferrite constituent (30-50%). When the hardening temperature is increased above the maximum steel hardening temperature, the quantity and the isolation of the ferrite constituent is increased (see Figure 2d and e). The 15Kh12VMF steel has a limited quantity of ferrite constituent (10-20%), which hardly undergoes any change even at high hardening temperatures (see Figure 2f and g). Steels 15Kh12V1MFBT and 15Kh12MFBT have no free ferrite, which is related to the effect of the nitrogen introduced through the nitrided ferrochromium (see Figure 2h).

An investigation of fractures of impact specimens, tested after various heat-treatments, showed that, as the hardening temperature and the quantity of the ferrite constituent are increased, the fracture changes from fine crystalline or fibrous to a coarsely crystalline; the impact strength, moreover, decreases.

All the steels tested were heat-treated so that approximately equal mechanical properties would be obtained. The heat-treatment (primarily the hardening temperature) was selected on the basis of a complex of characteristics obtained after experimental treatments (microstructure, mechanical properties, type of fracture, etc.).

Some steels (15Kh12MFB, 15Kh12MFBT, and 15Kh12VMFBT) were oil hardened at 900-920°. Other steels (15Kh12V1MFBT, 15Kh12MF, 15Kh12VMF, 25Kh12VF, and 25Kh12MF) were oil hardened at 950-1,000-1,020°. Before hardening at 1,020°, steel 15Kh12VMFT was normalized at 1,120°. Tempering was at 650-730° for 1-8 hours, depending on the characteristics of each steel.

The mechanical properties of the tested steels at 20-600° are listed in Table 2, where they are divided into three groups. The first group includes steels with an increased carbon content which have almost identical mechanical properties. Steels with an increased carbon content, however, have low impact strength at 20°, which strength is considerably increased at higher temperatures.

The second group includes steels containing less than 0.20% C; they are similar to the first-group steels in their mechanical properties but have a considerably greater impact resistance. Steel 15Kh12MFBT with nitrogen and boron is characterized by lower relative elongation and impact strength than the other steels in this group.

The steels in the third group, by comparison with the other groups, have generally inferior mechanical properties but a satisfactory impact strength. They, particularly steel 15Kh12VMFT, are characterized by a sharp impairment of mechanical properties when the temperature is increased.

The level of the mechanical properties of the steels tested is determined by the heat-treatment and is related to the structural state cited above. Insofar as mechanical properties are concerned, therefore, it is not possible to cite any one of the tested steels as being most advantageous.

Figure 3 illustrates the changes in the mechanical properties of the steels tested when soaked for 3,000 and 5,000 hours at 550° and 600°. In some steels, for example, 15Kh12V1FBT and 15Kh12V1MFBT, after 3,000 hours at 550°, the mechanical property characteristics remain unchanged, while in other steels (15Kh12MFB and 15Kh12MFBT) there is a tendency toward softening as impact strength is increased. There was no effect on the mechanical properties of steels 25Kh12VF, 25Kh12MF, and 15Kh12VMFT when they were soaked for 5,000 hours at 550°. Steels 15Kh12MF and 15Kh12VMF had a tendency toward partial softening.

An analysis of the structural state and mechanical properties of the experimental steels, after lengthy soaking, showed some regularity in degree of stability in relation to their initial state. After soaking for 3,000-5,000 hours at 550°, those steels were stable which had a yield point of 55-65 kg/mm² with the almost complete absence of free ferrite in the structure. Tendency toward softening appeared in steels whose yield point was not less than 70 kg/mm². Lengthy soaking for these steels apparently serves as a slow, lengthy, tempering which imparts a structural state of greater equilibrium to the steel.

A decrease in impact strength is also noted in steels having some ferrite constituent, which apparently results from dispersion hardening in the α phase. Steels containing a considerable amount of ferrite constituent, even with a low initial yield point (less than 60 kg/mm²), had a tendency toward stability loss.

It should be noted that soaking for 3,000-5,000 hours at 600°, regardless of the initial level of the properties or the structural state, has a softening effect on all the steels which, however, is decreased after 3,000 hours. The decrease in impact strength after soaking at 600° is also related to the dispersion hardening of the ferrite constituent. The character of the structural changes caused by lengthy soaking at 550-600° is shown in Figure 4. In steels which do not have any free ferrite in their structure (see Figure 4a), carbide formations emerge along the granular boundaries; the carbides are also separated in the form of a solid cord along the boundaries of the ferritic areas (see Figure 4b and c). The carbide inclusions then become spheroidal. Steels having a homogenous sorbitic-type structure underwent no change during this period. It may be assumed that the given character of carbide phase formation and its distribution along the granular boundaries is related to the decrease of impact strength during lengthy soaking.

The steels investigated were tested for creep. The creep curves at 550-600° at a stress of 10 kg/mm² are presented in Figures 5 and 6 for some of the steels, while the comparative results are listed in Table 3.

The data cited indicate that at 550-600° the 15Kh12VMF steel has the highest creep resistance. By eliminating tungsten (15Kh12MF) or by supplementary alloying this steel with ferrite-forming elements Nb and Ti (15Kh12MFBT and others), the creep resistance would be decreased.

It should be noted that, at 600°, steel with an increased carbon content (25Kh12MF) has a greater resistance to creep than the same steel but with a decreased carbon content (15Kh12MF). The 15Kh12V1MFBT steel, which contains both nitrogen and boron, is inferior in creep resistance at 600° to the 15Kh12VMF steel.

In continuous strength-to-destruction three steels are noteworthy: 15Kh12VMF, 15Kh12V1MFBT, and 15Kh12MF (see Figure 7). Steel with an increased carbon content (25Kh12MF) is inferior in continuous strength to the same steel (15Kh12MF) having a lower carbon content. The presence of Nb and Ti as well as W, Mo, and V in the steel, considerably decreases, as a result of ferritization, the time to destruction. However, in the presence of nitrogen and boron in such complexly alloyed steels (15Kh12V1FBT), the time to destruction is considerably increased. These steels behave the same way at 600°.

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Figure 8 shows the continuous strength-to-destruction curves at 550° for various stresses in the three steels cited. They are characterized by highly developed first and third periods of creep and high plasticity at destruction. All the specimens tested had an exclusively intracrystalline destruction. It should be noted that the 15Kh12VMF steel, tested for over 8,000 hours at 550° and $\sigma = 25 \text{ kg/mm}^2$, was in a state of steady-state creep for 7,000 hours, which creep was at a rate of $2.5 \times 10^{-4} \text{ \%/hour}$. The total deformation after 8,000 hours was 2.4%.

On the basis of the continuous strength-to-destruction data obtained from the three steels, a relationship may be established between stress and time to destruction, which may be used in establishing continuous strength limits (see Figure 9 and Table 4).

A comparison with steel 1Kh18N9T shows that the continuous strength limits at 550-600° of the investigated chromium heat-resistant steels and austenite steel 1Kh18N9T are about equal.

Conclusions

1. As a result of investigations conducted on steels alloyed with 12% chromium and various additional combinations of carbide-forming elements, as well as nitrogen and boron, it should be regarded as being established that the best heat-resistant characteristics are possessed by steels containing no structurally free ferrite or containing it in limited quantities, i.e., within the limits of 10-20%. The presence of over 30% ferrite sharply softens the steel and results in the loss of property stability.
2. From the experimental material presented it follows that, when equally alloyed, steel with a 0.15-0.18% carbon content possesses greater heat resistance than steel with 0.28% C. Alloying steel simultaneously with tungsten and molybdenum (15Kh12VMF) assures higher heat resistance than when alloying only with tungsten or only with molybdenum (15Kh12MF). Adding niobium or titanium to steel containing tungsten, molybdenum, and vanadium serves to ferritize the steel and to impair its heat resistance. Adding nitrogen helps to eliminate free ferrite in the steel and to increase its heat resistance.
3. Steels conditionally labeled as 15Kh12VMF, 15Kh12V1MFBT, and 15Kh12MF are recommended as being the most heat-resistant. These steels are recommended for long-term service at 550-600° in steam and gas turbine blades, disks, and other forgings.

REFERENCES

1. Dulis, E. J., Smith, G. V., Proceed. ASTM, v 53, 1953
2. Newhouse, D. L., Segnin, B. R., Lape, E. M., Trans. ASME, v 76, No 7, 1954
3. Clark, C. L., Metal Progress, v 65, No 1, 1954

Steel Grade	Chemical Composition (%)												Other
	C	Si	Mn	Cr	Ni	W	Mo	Y	Nb	Ti	S	P	
25KH12VF	0.28	0.24	0.64	13.7	0.4	1.2	--	0.3	--	--	0.028	0.030	
25KH12MF	0.28	0.25	0.70	13.15	0.2	--	0.54	0.22	--	--	0.030	0.023	
15KH12MF	0.18	0.25	0.70	13.0	0.22	--	0.60	0.20	--	--	0.028	0.028	
15KH12MFB	0.13	0.31	1.18	11.80	0.84	--	0.76	0.24	0.50	--	0.010	0.016	B 0.02
15KH12MFBT	0.11	0.04	0.12	12.4	--	--	0.79	0.43	0.20	0.12	0.011	0.02	N ₂ - nitrided ferro- chromium
15KH12VMF	0.17	0.22	0.64	13.15	0.20	0.85	0.46	0.20	--	--	0.028	0.024	
15KH12BMFT	0.18	0.38	0.76	12.9	0.20	1.0	0.47	0.24	--	0.13	0.028	0.023	
15KH12VMFBT	0.17	0.30	0.30	11.65	1.08	0.63	0.50	0.37	0.23	0.14	0.016	0.008	B 0.02
15KH12MFBT	0.18	0.56	0.22	12.3	--	1.2	0.70	0.54	0.15	0.12	0.017	0.026	N ₂ - nitrided ferro- chromium
15KH12V1FBT	0.16	0.33	0.73	11.8	1.22	1.05	--	0.40	0.28	0.23	0.010	0.019	

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Table 2. Mechanical Properties of Steels Investigated

Group	Steel	Test Temperature in °	$\sigma_{0.2}$ In kg/mm ²	σ_b In kg/mm ²	δ In %	γ In %	a_k In kgm/cm ²
I	25KH12VF	20	65.0	87.0	13.5--15.0	42.0--44.0	3.8--4.5
	25KH12MF	550	45.0	53.0	12.0--17.5	41.5--51.5	9.5--12.0
		600	30.5	35.5	25.0	83.5	11.5--12.5
II	15KH12MF						
	15KH12MFB						
	15KH12MFBT	20	62.5--74.0	79.0--87.0	14.5--18.0	46.5--62.5	7.0--13.0
	15KH12VMF	550	40.0--46.0	42.5--51.5	14.0--21.0	68.0--73.0	10.7--15.0
	15KH12VMFBT	600	30.0--39.0	33.5--42.5	13.0--24.5	69.5--79.5	10.0--17.6
	15KH12B1MFBT						
III	15KH12VMFT	20	55.0--62.5	74.0--76.0	16.5--20.0	55.5--61.5	5.5--9.3
	15KH12V1FBT	550	27.0--36.6	29.5--42.5	17.0--20.5	71.0--78.0	14.0--23.0
		600	18.5--28.5	22.0--31.0	20.0--34.0	80.0--85.0	15.8--24.6

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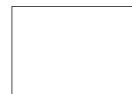


Table 3.
Comparative Results of Creep Tests of Experimental Steels

Steel Grade	Length of Test (hours)	Characteristics of Steady State Creep Area		Total Deformation (%)
		Length (hours)	Rate of Creep 10^{-4} %/hour	
550°, 10 kg/mm ²				
15KH12MF	1,300	800	2.2	0.54
15KH12VMF	2,050	1,550	2.6*	0.20
15KH12VMFBT	1,900	700	1.7	0.60
600°, 10 kg/mm ²				
25KH12VF	2,000	1,400	3.6	1.08
25KH12MF	1,830	1,430	4.5	1.22
15KH12MF	2,090	1,400	6.6	1.93
15KH12MFB	1,500	800	7.3	1.75
15KH12VMF	1,970	1,320	1.0	0.42
15KH12VMFT	120	--	--	1.20
15KH12V1MFBT	1,830	1,030	2.7	1.08

*Rate of creep is 10^{-5} %/hour

Table 4. Limits of Continuous Strength of Experimental Steels

Steel Grade	Limits of Continuous Strength in kg/mm ² at					
	550°			600°		
	1,000 Hours	10,000 Hours	100,000 Hours	1,000 Hours	10,000 Hours	100,000 Hours
15KH12MF	27	22.5	19	--	--	--
15KH12VMF	28--29	25	22	18.5	16	14
15KH12V1MFT						
1KH18N9T	--	24	20	--	--	13--15

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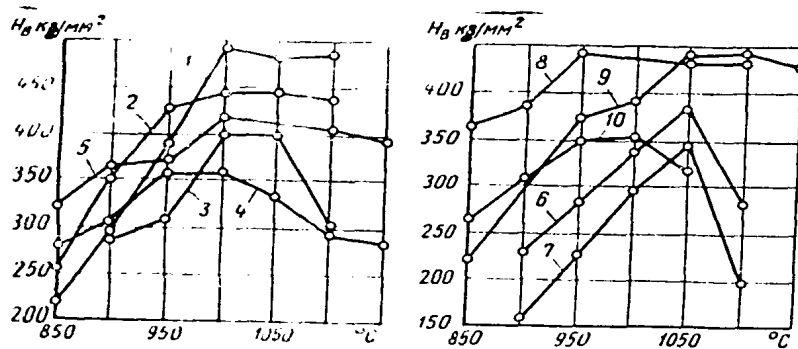


Figure 1. Hardness of test steels when hardened from various temperatures: (1) 25Kh12VF; (2) 25Kh12MF; (3) 15Kh12MF; (4) 15Kh12MFB; (5) 15Kh12MFBT; (6) 15Kh12VMF; (7) 15Kh12VMFT; (8) 15Kh12VMFBT; (9) 15Kh12V1MFBT; (10) 15Kh12V1FBT.

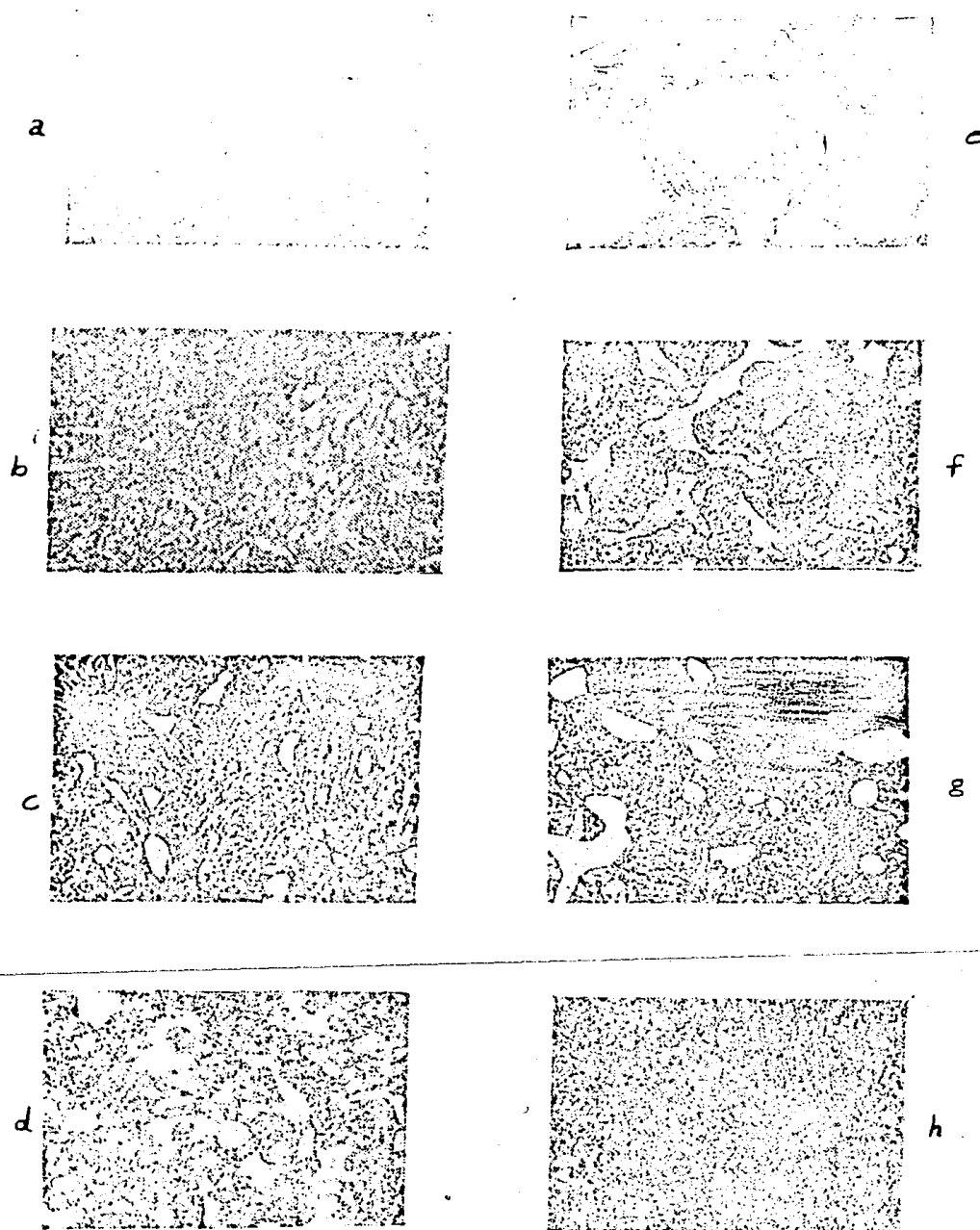


Figure 2. Microstructure of Investigated Steels (X300):

- (a) 25Kh12MF, hardened at $1,000^{\circ}$, tempered at 700° ;
- (b) 25Kh12MF, hardened at $1,050^{\circ}$, tempered at 700° ;
- (c) 15Kh12MF, hardened at $1,050^{\circ}$, tempered at 700° ;
- (d) 15Kh12VMFT, hardened at $1,000^{\circ}$, tempered at 700° ;
- (e) 15Kh12VMFT, hardened at $1,250^{\circ}$, tempered at 700° ;
- (f) 15Kh12VMF, hardened at $1,050^{\circ}$, tempered at 700° ;
- (g) 15Kh12VMF, normalized at $1,050^{\circ}$, hardened at $1,050^{\circ}$, tempered at 700° ;
- (h) 15Kh12MFBT, hardened at 950° , tempered at 690° .

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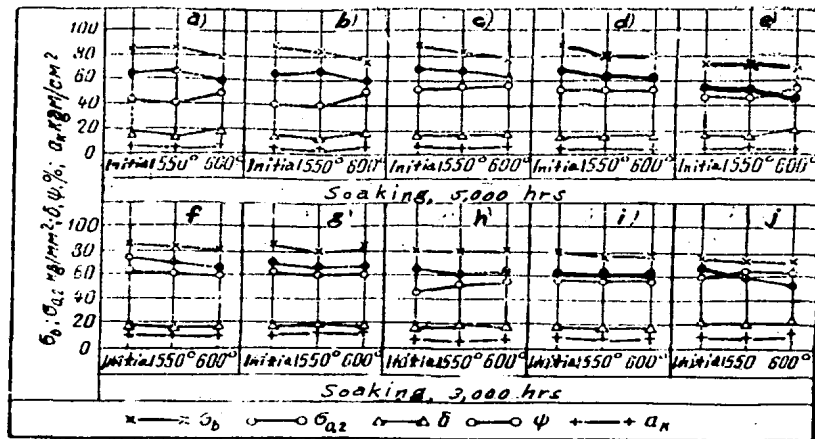


Figure 3. Effect of soaking for 3,000 and 5,000 hours at 550-600° on the mechanical properties at 20° of the following steels:
 (a) 25Kh12VF; (b) 25Kh12MF; (c) 15Kh12MF;
 (d) 15Kh12VMF; (e) 15Kh12VMFT; (f) 15Kh12MFB;
 (g) 15Kh12MFBT; (h) 15Kh12MFBT; (i) 15Kh12V1MFBT;
 (j) 15Kh12V1FBT.



a



c



b

Figure 4. Microstructure of some steels after lengthy soaking:
 (a) 15Kh12V1MFBT, 550°, 3,000 hours;
 (b) 15Kh12VMFT, 600°, 5,000 hours;
 (c) 15Kh12VMF, 600°, 5,000 hours.

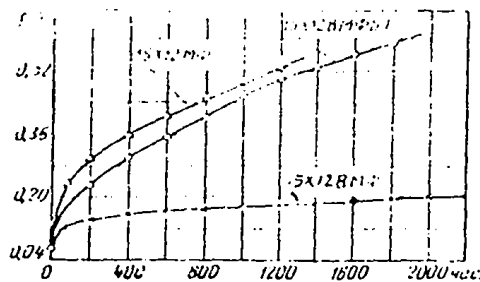


Figure 5. Creep of steels at 550°, $\sigma = 10 \text{ kg/mm}^2$

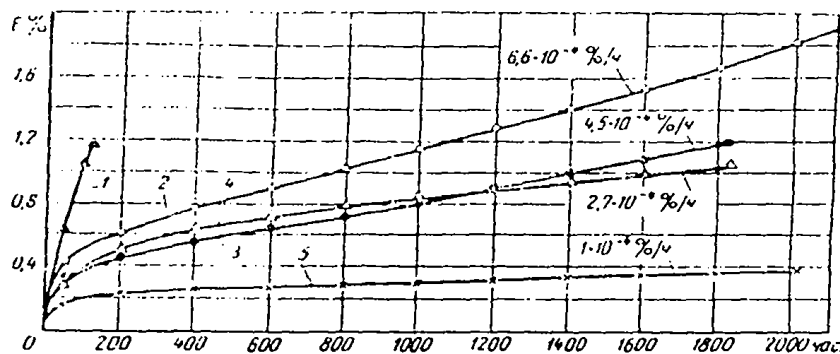
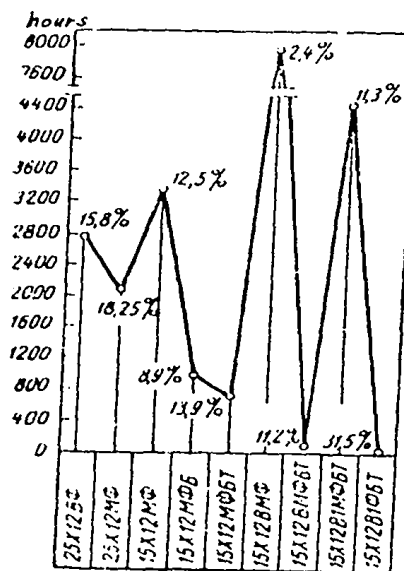


Figure 6. Creep of steels at 600°, $\sigma = 10 \text{ kg/mm}^2$:
 (1) 15Kh12VMΦT; (2) 15Kh12MF; (3) 25Kh12MF;
 (4) 15Kh12V1MFΦT; (5) 15Kh12VMΦ.

Figure 7. Comparison of time to destruction at 550°, $\sigma = 25 \text{ kg/mm}^2$



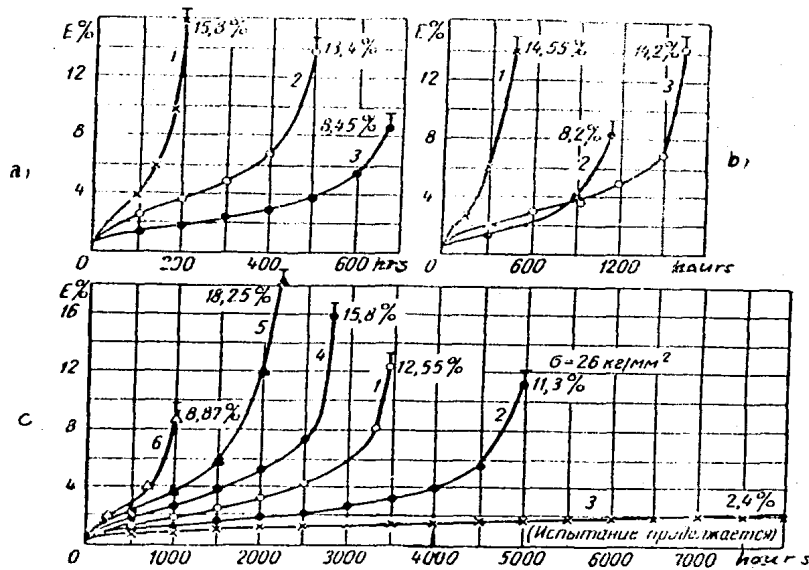


Figure 8. Curves of long-time rupture at 550°C for some steels:
 (a) 30 kg/mm²; (b) 28 kg/mm²; (c) 25 kg/mm²;
 (1) 15Kh12MF; (2) 15Kh12VMFB; (3) 15Kh12VMF;
 (4) 25Kh12VF; (5) 25Kh12MF; (6) 15Kh12MFB.

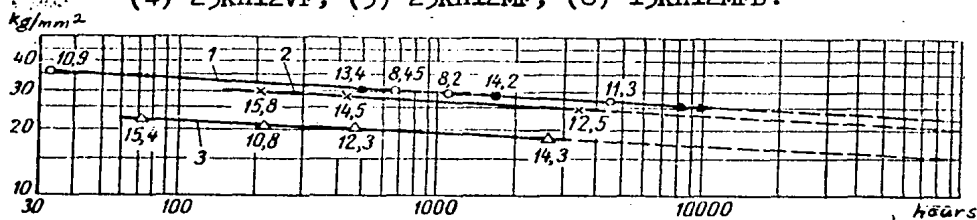


Figure 9. Continuous strength of some steels:
 (1) 15Kh12VMF and 15Kh12VMFBT, 550°C;
 (2) 15Kh12MF, 550°C; (3) 15Kh12VMF, 600°C.

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